

NASA CASE NO. NPO-16,420-1
PRINT FIG. 8

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N86-20681

(NASA-Case-NPC-16420-1) BRUSHLESS DC MOTOR
CONTROL SYSTEM RESPONSIVE TO CONTROL SIGNALS
GENERATED BY A COMPUTER OR THE LIKE Patent
Application (NASA) 39 P HC A03/MF A01
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8 BRUSHLESS DC MOTOR CONTROL SYSTEM
9 RESPONSIVE TO CONTROL SIGNALS
10 GENERATED BY A COMPUTER OR THE LIKE

11
12 BACKGROUND OF THE INVENTION

13 1. Origin of the Invention

14 The invention described herein was made in the
15 performance of work under a NASA Contract and is subject
16 to the provisions of Section 305 of the National Aeronau-
17 tics and Space Act of 1958, Public Law 85-568 (72 STAT
18 435; 43 USC 2457).

19
20 2. Field of the Invention

21 This invention relates to direct current (DC)
22 motor control systems, and more particularly to systems
23 for controlling brushless DC motors in response to
24 digital control signals generated by a microprocessor,
25 computer or the like.

26
27 3. Brief Description of the Prior Art

28 Computers and microprocessors have found wide-
29 spread use in control systems. Such control systems
30 often utilize electric motors, e.g., of the DC brush or
31 brushless type, to perform a variety of tasks such as
32 positioning members, e.g., antennas, solar arrays, etc.
33 However, conventional motors require extensive addi-
34 tional electronic circuitry in order to interface with
35

1 the computers or microprocessors. The additional elec-
2 tronics may include a power module for translating
3 feedback signals of servo modules, tachometers, shaft
4 encoders, feedback summing boxes and potentiometers for
5 providing appropriate shaft position, speed, etc. The
6 use of such components to translate the digital signals
7 from the microprocessor into the voltages and currents
8 is necessary to drive the motors and increases the
9 complexity, cost, size and weight of the control system.

10 In addition to adding to cost, etc., the
11 control system designers often have to design the
12 circuitry internal to many such components to provide
13 the desired motor performance. Where the rate or speed
14 at which the motor shaft advances from one position to
15 another must be controlled, the designer will generally
16 have to make a tedious selection from available shaft
17 position sensors such as tachometers, encoders, etc., to
18 achieve the best match since the manufacturers of the
19 motor and shaft position sensors seldom design one compo-
20 nent specifically for the other. Very often a compro-
21 mise is the best that the designer can accomplish.
22 These accessory components needed to interface a source
23 (composite) of low level digital signals with electric
24 motors also add undesired inertia and friction to the
25 systems. The inertia and resistance of these accessory
26 items may exceed that of the load desired to be driven.

27 U.S. Patent No. 4,249,116 advocates the use of
28 a programmable oscillator as an interface between a
29 brushless DC motor and a computer to provide some measure
30 of torque and speed control. However, the control
31 system disclosed in the '116 patent is not only complex,
32 but unsuitable for incremental position (stepping)
33 control or for rate (speed) and torque control during
34 transitions, i.e., between zero and the desired rate.
35

1 Incremental position control has been achieved
2 by stepper motors and their associated digital controls.
3 While such motors and their controls are reasonably
4 simple and reliable, they raise other problems, such as
5 increased power requirements, slow speed operation and
6 low torque sensitivity. The present invention solves
7 the above problems by providing a DC brushless electric
8 motor and control system which is responsive to low
9 power level digital control signals from a computer or
10 microprocessor to cause the motor to step to a desired
11 position or run continuously at a controlled rate and
12 torque, reverse direction and synchronize itself with
13 other motors.

14
15 SUMMARY OF THE INVENTION

16 In accordance with the present invention, a DC
17 brushless motor and control system adapted to be ener-
18 gized from a source of direct current and controlled in
19 response to digital signal from a function generator,
20 such as a computer or microprocessor, is provided. The
21 motor includes a shaft carrying a permanent magnet rotor
22 and a multiphase wound stator. The rotor and stator are
23 arranged so that each phase winding when energized
24 (during its commutation period) from the DC source
25 causes the rotor to step or advance through a predeter-
26 mined angular position. Shaft position-sensing means
27 are provided to derive shaft position signals indicative
28 of the angular position of the motor shaft.

29 A commutation signal generator is responsive
30 to the shaft position signals for generating commutation
31 signals representative of the commutation period for
32 each phase winding of the motor. Driving means which
33 may, for example, be in the form of semiconductor
34 switches are individually associated with each phase
35 winding for selectively applying current from the DC

1 source to the associated winding. Gating means, which
2 may conveniently be in the form of AND gates, are indi-
3 vidually connected to the driving means for each phase
4 winding. Each gating means is responsive to the commuta-
5 tion and digital control signals (from the computer) for
6 the respective phase winding for enabling the associated
7 driving means to apply current to the respective winding
8 only upon the occurrence of the commutation signal and
9 the control signal for the winding.

10 The motor may be incrementally advanced to any
11 selected position, as determined by the control signals
12 applied to the gating means to set the number of times
13 that each phase winding is connected to the DC source,
14 or the motor may be run continuously. The rate at which
15 the motor steps or advances from one position to another
16 may be controlled by varying the repetition rate of the
17 control signals (step command pulses) applied to the
18 gating means. In addition to controlling the rate at
19 which the motor advances from one position to another,
20 the computer may be programmed to apply a plurality of
21 torque-regulating pulses to the gating means during each
22 commutation period. The torque-regulating pulses
23 control the total time duration in which each driving
24 means applies current from the DC source to the
25 associated winding during each commutation period.

26 The novel features of the invention are set
27 forth with particularity in the appended claims. The
28 invention may be best understood from the following
29 description when read in conjunction with the accom-
30 panying drawings.

31 BRIEF DESCRIPTION OF THE DRAWINGS

32 Figure 1 is an elevational view, partially
33 broken away, of a prior art brushless DC motor and a
34 control circuit therefore;
35

1 Figure 2 is a cross-sectional view of the
2 motor of Figure 1 taken along lines 2-2;

3 Figure 3 is a cross-sectional view taken along
4 lines 3-3 of Figure 2 of a rotor position sensor incor-
5 porated in the motor of Figure 1;

6 Figure 4 is an end view taken along lines 4-4
7 of Figure 3 of one of the magnets of the rotor position
8 sensor with the magneto resistors secured to the face
9 thereof;

10 Figure 5 is a schematic circuit diagram of the
11 electronic control circuit incorporated in the motor of
12 Figure 1;

13 Figure 6 is a waveform diagram illustrating
14 the waveform of the pulses present at various points in
15 the circuit of Figure 5 for clockwise rotation of the
16 motor shaft;

17 Figure 7 is another waveform diagram illustrat-
18 ing the waveform of the pulses present at various points
19 in the circuit of Figure 5 during counterclockwise
20 rotation of the motor shaft;

21 Figure 8 is a schematic circuit diagram of an
22 embodiment of a motor control system in accordance with
23 the present invention with certain elements of the
24 circuit of Figure 5 left out for simplicity;

25 Figure 9 is a waveform diagram illustrating
26 the waveform of certain signals present in the circuit
27 of Figure 8;

28 Figure 10 is a combined block and schematic
29 circuit diagram of another embodiment of the present
30 invention for controlling the motor position;

31 Figure 11 is a schematic circuit diagram of
32 another embodiment of the present invention for providing
33 a desired torque profile for the motor;
34
35

1 Figure 12 is a diagram of one speed/torque/
2 current profile of a motor controlled by the system of
3 Figure 11;

4 Figure 13 is a combined block and schematic
5 circuit diagram of another embodiment of the present
6 invention in which the speed of the motor is controlled
7 between two limits;

8 Figure 14 is a block diagram of another embodi-
9 ment of the present invention for synchronizing the
10 operation of three motors;

11 Figure 15 is a schematic circuit diagram
12 showing the internal connections to the motor circuit
13 for synchronizing a plurality of motors in accordance
14 with the block diagram of Figure 14; and

15 Figure 16 is a schematic circuit diagram
16 showing one phase winding of three separate motors in
17 accordance with the motor control system of Figures 14
18 and 15.

19
20 DETAILED DESCRIPTION OF THE DRAWINGS

21 Referring now to the drawings, in which the same
22 numerals are used in the several figures to identify the
23 same element, and particularly to Figure 1, there is
24 illustrated a prior art three-phase brushless DC motor 14
25 which includes a case 15, a shaft 16, a rotor 17 and a
26 stator 18. The motor includes a magnetic detent assembly
27 comprising a stationary portion 20 and a rotating por-
28 tion 22. The magnetic detent assembly is conventional
29 and includes a plurality of small permanent magnets
30 spaced at 10-degree increments around the shaft to stop
31 the motor at one of the 10° positions and prevent a load
32 connected to the shaft (through gearing) from causing
33 the motor to reverse.

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1 The motor includes a rotor or shaft position
2 sensor in the form of a rotating target 24 connected to
3 the shaft 16 and three stationary permanent magnets 26,
4 as is shown more clearly in Figure 3. Three printed
5 circuit boards 28, 29 and 30 are mounted in the
6 housing 12 and contain the control electronics to permit
7 the motor to operate as a brushless DC motor. Power
8 input leads 32 and 34 extend from the case 15 for connec-
9 tion through a suitable electronic power module to a
10 source of DC voltage. Lead 36 is connected to the case
11 ground. Leads 38 and 39 are connected across a small
12 resistor in series with the neutral leg of the motor
13 windings to provide a voltage proportional to the
14 current drawn by the motor, as will be explained in
15 connection with Figure 5.

16 Referring now to Figure 2, the stator 18
17 includes 12 winding slots (numbered 1 through 12) to
18 provide a full coil configuration and a directional
19 change in current at each 90° of angular position. The
20 winding for phase 1 is identified by the numeral 40 and
21 is located in slots 1, 10, 4 and 7. Winding 42 for
22 phase 2 is located in slots 3, 6, 9 and 12, and winding 44
23 for phase 3 is located in slots 2, 5, 8 and 11.

24 Four permanent magnets 46, 47, 48 and 49 are
25 mounted on the shaft and oriented at 90° with alter-
26 nating north and south poles, as shown. This permits
27 the magnetic flux from the rotor to couple to the stator
28 coil at four positions around the stator. The rotor
29 magnets are sized to cover a 60° span or step at each of
30 the 90° positions of the shaft. With this arrangement,
31 one set of stator coils (one phase winding) will generate
32 magnetic torque for 60° of shaft rotation. Each set of
33 stator coils is displaced from the other sets by 60°
34 around the stator circumference, as illustrated. With
35 phase sequence control of the current to the stator

1 coils, each phase will generate torque for 60° of shaft
2 rotation, and the three phases will provide torque
3 generation corresponding to 180° shaft rotation. The
4 phase sequence is repeated for a full 360° of shaft rota-
5 tion or one complete revolution. A commutation signal
6 must be provided for each 60° of shaft rotation, and the
7 signal must be in proper phase sequence to provide a
8 continuous rotating current in the stator windings and
9 the necessary rotating field.

10 Figure 3 illustrates an end view of the rotor
11 or shaft position sensor. The sensor includes a target 24
12 carried by the shaft 16, which is made of a ferromag-
13 netic material such as soft iron with a pair of lobes 24a
14 and 24b. The stationary portion 26 of the rotor posi-
15 tion sensor includes three permanent magnets 26a, 26b
16 and 26c spaced around the rotor shaft at 120° positions,
17 as illustrated. A pair of magneto resistors are carried
18 on the face of each of the permanent magnets 26a-26c
19 adjacent the target 24. As is illustrated in Figures 3
20 and 4, magneto resistors 52a and 52b are mounted on the
21 face of magnets 26a and 26b; magneto resistors 54a and
22 54b are mounted on the face of magnets 26b and 26c; and
23 magneto resistors 56a and 56b are mounted on the face of
24 magnets 26c and 26a, as shown.

25 Referring now to Figure 4, there is illustrated
26 the manner in which the magneto resistors 52a and 56b are
27 mounted on the face of the permanent magnet 26a. The
28 magneto resistors are semiconductor elements that provide
29 an increase in resistance when they are exposed to an
30 increased magnetic flux. The proximity of the rotor
31 target 24 to each magneto resistor governs its relative
32 resistance. The magneto resistors are connected to form
33 the legs of a bridge network, as is illustrated more
34
35

1 particularly in Figure 5, so that as the target rotates
2 a shaft position signal is generated which is indicative
3 of the shaft position.

4 Referring now to Figure 5, there is illustrated
5 the control electronics for the motor of Figures 1
6 through 4. The phase windings 40, 42 and 44 of the
7 motor are connected in a star configuration, as shown,
8 with a neutral leg 60 connected to the junction of the
9 three windings. The neutral leg 60 is connected to an
10 output terminal 62 of a full wave rectifier bridge 64.
11 The other output terminal 66 of the bridge 64 is
12 connected to ground through an armature current sensing
13 resistor 67. A suitable source of DC power is applied
14 to the input of the bridge 64 by means of power input
15 leads 32 and 34.

16 Darlington configuration switching transis-
17 tors 72a/72b, 74a/74b and 76a/76b are individually con-
18 nected in series with each phase winding for selectively
19 applying current to the associated winding from the
20 power source connected to the terminals 32 and 34, as
21 will be explained. Each pair of switching transistors
22 is sometimes hereinafter referred to as driving means
23 for selectively applying current to associated phase
24 winding of the motor. The driving means for the phase 1
25 winding comprises transistors 72a and 72b with a pair of
26 resistors connected between the emitter and base elec-
27 trodes of each transistor, as illustrated. Transis-
28 tors 74a and 74b comprise the driving means for the
29 second phase winding, and transistors 76a and 76b comprise
30 the driving means for the third phase winding. Leads D1,
31 D2 and D3 connect the phase windings 40, 42 and 44 to
32 the collector electrodes of the transistors 72a, 74a and
33 76a, respectively.
34
35

1 Separate pairs of the shaft position sensor
2 elements (magneto resistors) 52a through 56b are connected
3 in series between terminals 78 and 79, as illustrated,
4 with the junctions RP-1, RP-2 and RP-3 of each pair con-
5 nected to separate negative inputs of a comparator 80.
6 The comparator 80 includes three high gain operational
7 amplifiers 80a, 80b and 80c, and an additional opera-
8 tional amplifier which is not used. A reference voltage
9 is applied to the positive input to each of the opera-
10 tional amplifiers 80a, 80b and 80c by means of the resis-
11 tors 82a-86b. The positive input to the amplifier 80a
12 is connected to the junction of resistors 82a and 82b.
13 The positive input of the amplifier 80b is connected to
14 the junction of resistors 84a and 84b, and the positive
15 input to the amplifier 80c is connected to the junction
16 of resistors 86a and 86b. Each pair of resistors 82a/82b,
17 84a/84b and 86a/86b is connected in parallel with the
18 pairs of shaft position sensor elements 52a/52b, etc.,
19 to form three separate bridge circuits.

20 The terminals 78 and 79 of the bridge circuits
21 are connected to the input power terminals 32 and 34
22 through resistors 94 and 96, as shown. A pair of addi-
23 tional resistors 98 and 100 connects the terminals 78
24 and 79 to ground, respectively.

25 The target 24 (carried by the rotor) changes
26 the resistance of the shaft position sensor elements 52a
27 through 56b as the shaft rotates. As a result, the
28 voltages (in the millivolt range) at terminals RP-1,
29 RP-2 and RP-3, representing the shaft position, change,
30 and this change are compared with the reference voltages
31 across the balanced legs of the bridges (resistors 82a-
32 86b) by the comparator 80. The output signal on output
33 terminals C-1, C-2 and C-3 of the amplifier 80a-80c
34 provides a three-phase commutation signal for driving
35 the transistors 72a-76b in proper sequence to provide a

1 rotating field in the stator. Any overlap of these
2 output signals due to the target configuration of the
3 shaft position sensor (thereby providing overlapping
4 commutation signals) is prevented by feedback from the
5 driving transistors, as will be explained.

6 The output signals on terminals C-1, C-2 and
7 C-3 of the comparator 80 are applied across the base
8 emitter junctions of transistors 72b, 74b and 76b
9 through zener diodes 102, 104 and 106 (to prevent prema-
10 ture turn-on of the transistor), as shown.

11 Cross-strapping diodes 108, 110 and 112 are
12 connected between the collectors of the switching tran-
13 sistors 72a, 74a and 76a, and the output terminals C-1,
14 C-2 and C-3 of the comparator 80, as illustrated, to
15 ensure that (1) only one pair of Darlington transistors
16 will be switched on at any time; and (2) the commutation
17 signals from the comparator 80 are coextensive with the
18 angular rotation of the shaft (e.g., 60°) resulting from
19 the energization of the associated phase winding. This
20 prevents the energization of more than one stator
21 winding at a time. The diode 108 is connected to the
22 junction of a pair of resistors 114a and 114b, which
23 resistors are connected in series between the output
24 terminal C-1 and the output terminal 62 of the diode
25 bridge 64. The diodes 110 and 112 are in similar
26 fashion connected to the junction of resistors 116a and
27 116b and 118a and 118b, respectively, with these transis-
28 tors being connected between the terminal 62 and the
29 output terminals C-2 and C-3, as shown.

30 Referring now to Figure 6, the waveforms RP-1,
31 RP-2 and RP-3 represent the shaft position signals
32 appearing on output leads RP-1, RP-2 and RP-3 of the
33 circuit of Figure 5. Each of the signals appearing at
34 these leads completes one cycle during 180° of shaft
35 rotation. The shaft position signals are displaced from

1 each other by 60° , as is illustrated in Figure 6. The
2 voltage waveforms C-1', C-2' and C-3' (no diode clamping)
3 represent the voltages that would appear on the output
4 of the comparator terminals C-1, C-2 and C-3 absent the
5 clamping action of the diodes 108, 110 and 112. The
6 comparator 80 has a high gain and effectively converts
7 the shaft position signals into square waves. The
8 clamping diodes 108, 110 and 112 clamp each of the
9 output terminals C-1, C-2 and C-3 of the comparator 80
10 to substantially ground points during the time that the
11 preceding winding is energized. For example, diode 108
12 clamps the output terminal C-1 to substantially ground
13 potential when the phase 2 winding is energized by
14 transistor 74a, etc. Waveforms C-1, C-2 and C-3 in
15 Figure 6 (diode clamping) demonstrate the actual signals
16 present at the respective output terminal with the
17 diodes 108, 110 and 112 present. Waveforms D-1, D-2 and
18 D-3 represent the voltage present across the driving
19 transistors 72a, 74a and 76a, respectively, and hence
20 the energization of the respective stator windings.

21 To reverse the direction of the motor, it is
22 simply necessary to reverse the polarity of the DC input
23 power applied to terminals 32 and 34. As will be noted,
24 the diode bridge 64 maintains the same polarity across
25 the driving transistors 72a-76b, and hence the same
26 direction of current flow through the stator windings.
27 Reversal of the polarity of the input power reverses the
28 polarity across the shaft position sensor bridges or
29 terminals 78 and 79. This results in a reversal of the
30 signal phase input to the comparator, causing the driving
31 transistors to effectively reverse the sequence of opera-
32 tion, thereby reversing the direction of the motor.

33 Figure 7 illustrates the waveforms present in
34 the circuit of Figure 5 with the input power polarity
35 reversed to provide a counterclockwise rotation of the

1 motor. On an initial reversal of the input power, the
2 motor's first step in the opposite direction will be
3 through a 30° angle. From then on, the motor will step
4 in 60° increments, as will become apparent from Figures 6
5 and 7.

6 The motor of Figures 1, 2 and 5 is manufac-
7 tured by Aeroflex Laboratories of Plainview, New York.
8 The motor is controlled by varying the amplitude and
9 polarity of the supply voltage applied to terminals 32
10 and 34. As discussed previously, this requires that
11 various control components, such as power control boxes,
12 feedback summing boxes, etc., be matched as closely as
13 possible to the motor. Such components and the neces-
14 sity to match them to the characteristics of the motor
15 are eliminated by the present invention.

16 Referring now to Figure 8, an embodiment of
17 the present invention is illustrated for controlling the
18 motor of Figures 1-4 in response to low level (e.g.,
19 0-5 volts) digital signals from computers or micro-
20 processors. It should be noted that many of the circuit
21 elements of Figure 5 are not included in Figure 8 for
22 sake of simplicity. In accordance with the invention,
23 gating means in the form of AND gates 120, 122 and 124
24 are individually connected, as shown, between the output
25 terminals of the comparator 80 and the input to the drive
26 transistors for each phase winding. The AND gate 120 is
27 connected between the output terminal C-1 of the compara-
28 tor 80 and the input to the transistor 72b for phase
29 winding No. 1. AND gate 122 is connected between the
30 output terminal C-2 and the input to the transistor 74b
31 for the second phase winding, and gate 124 is connected
32 between the output terminal C-3 and the input to the
33 transistor 76b.

1 Each of the AND gates receives the commutation
2 signal for the associated phase winding and input signals
3 from a programmable control signal generator 130. The
4 control signal generator 130 may be in the form of a
5 computer or microprocessor which provides low-level
6 digital signals for enabling the AND gates 120, 122 and
7 124 to incrementally position the motor 13 and control
8 the torque generated therein as desired hereinafter.
9 These control signals include step command pulses on
10 leads SC-1, SC-2 and SC-3 and torque regulation pulses
11 on leads TR-1, TR-2 and TR-3. The circuit of Figure 8
12 includes, in addition to the elements of Figure 5 (1)
13 the AND gates 120, 122 and 124; (2) the control signal
14 generator 130; (3) a voltage regulator consisting of a
15 capacitor 132 (connected across the output of the diode
16 bridge 64) and a zener diode 134 (connected between
17 ground and the power supply terminal to the compara-
18 tor 80); and (4) a pair of zener diodes 136 connected
19 across each stator winding to suppress transient voltages.

20 The drive transistors associated with each of
21 the AND gates 120-124 will turn on to thereby supply
22 current to the respective stator winding only when all
23 of the inputs to that AND gate are positive. Where
24 incremental positioning of the motor only is desired,
25 then AND gates 120, 122, and 124 can simply be provided
26 with three inputs; that is, one input for receiving the
27 commutation signals from the comparator 80, one input
28 for receiving the step command pulses from the control
29 generator 130 and one input for receiving the torque-
30 regulating pulses from the control generator 130. With
31 such an arrangement, the shaft of the motor will begin
32 to rotate when all of the inputs to an AND gate become
33 positive, and rotation will continue until the compara-
34 tor 80 switches its high level output to the next stator
35 coil or until the step command pulse input is terminated.

1 Thus, failure to complete a step will not cause a torque
2 dropout because as the sequential step command pulses
3 continue, full motor torque will again be developed. By
4 the same token, a long step command pulse can be used
5 without danger of excessive power dissipation within the
6 motor because the comparator input (commutation signal)
7 to the gate will drop to zero as soon as 60° of shaft
8 rotation occurs, thereby terminating the drive signal to
9 that transistor pair, regardless of the status of the
10 step command pulses. The motor may be stepped at any
11 desired speed within the limits of the electrical time
12 constant of the motor by simply adjusting the pulse
13 repetition rate of the step command pulses. When the
14 step command pulses become a continuous signal applied
15 to all three AND gates, the motor will simply operate as
16 a conventional brushless DC motor.

17 The amount of current supplied to the stator
18 windings during the step command pulses determines the
19 torque produced by the motor. By providing torque-
20 regulating pulses from the signal control generator 80
21 on leads TR-1, TR-2 and TR-3 which have a controllable
22 width (pulse width modulation), the magnitude of the
23 current supplied to the stator windings during each
24 commutation period can be regulated. The torque-
25 regulating pulses must have a repetition rate which is
26 higher than the repetition rate of the step command
27 pulses. For example, the repetition rate of the torque-
28 regulating pulses may be ten times the repetition rate
29 of the step command pulses. The duty cycle of the
30 torque-regulating pulses determines the total on time
31 for each drive transistor pair and the total amount of
32 energy applied to the load during each step. The
33 current sensing resistor 67 of Figure 5 may be used in a
34 feedback circuit for permitting the torque profile of
35

1 the motor to be tailored to any desired function within
2 the limits of the motor, as will be explained more fully
3 hereinafter.

4 It should be noted that the control system of
5 this invention will operate brushless motors of two
6 phases, three phases or more. Various types of shaft
7 position sensors, drive transistors, etc., may also be
8 used in place of the arrangement shown in Figures 1-5.

9 Referring now to Figure 9, there are illus-
10 trated the waveforms of certain of the signals present
11 in the circuit of Figure 8. The waveforms SC-1, SC-2
12 and SC-3 represent the waveforms of the step command
13 pulses on leads SC-1, SC-2 and SC-3. The waveforms C-1,
14 C-2 and C-3 represent the commutation signals from the
15 comparator 80, as has been explained in connection with
16 Figures 6 and 7. Waveforms D-1, D-2 and D-3 again repre-
17 sent the waveforms of the voltages appearing at the
18 terminals D-1, D-2 and D-3. The waveforms TR-1, TR-2 and
19 TR-3 represent the waveforms of the torque-regulating
20 pulses on terminals TR-1, TR-2 and TR-3. It should be
21 noted that a uniform pulse train to input commands (SC-1,
22 SC-2 and SC-3) is not required. Incremental control of
23 positioning can be achieved at any desired rate.

24 Referring now to Figure 10, there is illus-
25 trated a simplified system for controlling the position
26 of the motor shaft. In this embodiment, the commutation
27 signals on leads C-1, C-2 and C-3 are applied to the
28 input of an OR gate 140, the output of which is applied
29 to a programmable control signal generator 142, e.g., a
30 microprocessor. The other input to the microprocessor
31 is an address word from a serial position address
32 generator 144. The output from the OR gate 140 will
33 consist of six pulses for each revolution of the motor.
34 The serial string of pulses from the OR gate 140 may be
35 provided to a serial-to-parallel converter within the

1 programmable control signal generator 142 to provide a
2 binary word proportional to the number of pulses from
3 the OR gate 140. The binary address word provided by
4 the generator 144 is compared by the generator 142 to
5 the binary word resulting from the output of the OR
6 gate 140. If the binary address word is different than
7 the binary word generated from the OR gate output, the
8 generator 142 will supply step command pulses (similar
9 to pulses SC-1, SC-2 and SC-3 of Figure 9) to the AND
10 gates 120, 122 and 124 to drive the motor. It should be
11 noted that the third input to each AND gate 120, 122 and
12 124 is connected to a positive potential, as illustrated,
13 so that the two remaining inputs control the output.
14 The AND gates thus become effectively two-input gates.

15 When the binary word generated from the
16 commutation signals equals the binary address word, the
17 step command pulses to the motor will stop and the motor
18 will be at the desired position. If the binary word
19 generated from the commutation signals is smaller than
20 the address word, step command pulses with the proper
21 sequence will be provided to the AND gates 120-124 to
22 increase the generated binary word and vice versa. When
23 the motor 14 is connected to the load through a set of
24 gears having a high gear ratio, e.g., 880:1, the posi-
25 tion of the load can be very accurately controlled,
26 e.g., 2^{12} position increments per revolution.

27 Torque-regulating pulses from the generator 142
28 (e.g., microprocessor) can be provided on the third
29 input to the AND gates for torque control, as discussed
30 in connection with Figure 8.

31 Figure 11 illustrates another embodiment of
32 the present invention in which the torque profile of a
33 continuously running motor is programmed to follow a
34 linear curve. The commutation signal associated with
35 one phase, in this case phase 3, is applied to a single

1 retriggerable multivibrator 144. The multivibrator 144
2 may be of the type manufactured by a number of manufac-
3 turers, including the National Semiconductor Corp., under
4 Part No. 74122. The commutation signal is applied to
5 terminal No. 3 of multivibrator 144, as shown. A timing
6 capacitor 146 and a timing resistor 147 are connected to
7 terminals 11, 13 and 14. The output signal on terminal 8
8 is a pulse initiated by the commutation signal and having
9 a repetition rate determined by the frequency of the
10 commutation signal and width determined by the capaci-
11 tor 146 and the resistor 147. The capacitor 146 may have
12 a value of 1 microfarad, and the resistor 147 has the
13 value of 9 kilohms. With these component values, the
14 output pulse will have a time duration of .0031 second,
15 which is one-half the time required for one armature
16 revolution at 10,000 rpm. With two commutation pulses
17 per revolution, the pulse duration is .0061 seconds,
18 which is the time for one revolution. Thus, the commuta-
19 tion pulse from one phase will result in a continuous
20 output DC signal from the multivibrator 144 consisting
21 of a series of .0031-second pulses attached together in
22 time sequence when the motor speed is 10,000 rpm. This
23 is equivalent to a 100% duty cycle. As the motor slows
24 down, the duty cycle will decrease to, for example, 50%
25 when the motor is running at 5,000 rpm.

26 The output pulses from the multivibrator 144
27 (on pin 8) are integrated by a resistor 148 and a capaci-
28 tor 150. The resultant voltage across capacitor 150
29 will vary with the frequency or pulse repetition rate of
30 the commutation signal. This linear voltage varies from
31 0 to 4 volts (for the component values chosen) and is
32 inserted at pin 9 of a pulse generator 152. This pulse
33 generator 152 may be of the type manufactured by Silicon
34 General Corp. under Part No. 1524B. The output of the
35 pulse generator from pin 14 is a series of pulses with a

1 width which varies with the amplitude of the voltage
2 applied to pin 9. These output pulses are applied as
3 one input to each of the AND gates 120, 122 and 124, as
4 shown. The third input of these AND gates is not shown
5 but would be connected to a positive potential source as
6 was discussed with respect to Figure 10. The frequency
7 of the output pulses from generator 152 is determined by
8 the values of a resistor 154 and a capacitor 156 connected
9 in series across pins 6 and 7. The frequency of the
10 output pulses should be on the order of ten times the
11 frequency of the commutator pulses at the maximum anti-
12 cipated motor speed. A current limit control is built
13 into the generator 152 and responds to a voltage across
14 pins 4 and 5 to start limiting the width of the output
15 pulses when the voltage level reaches 200 millivolts. A
16 voltage divider in the form of a pair of resistors 158
17 and 160 may be connected across the current sensing
18 resistor 67 so that the voltage between the junction 159
19 of these resistors and ground will be 200 millivolts
20 when the motor current reaches its maximum value. When
21 the motor current exceeds its allowable maximum value,
22 the generator 152 will reduce the width of the output
23 pulses as necessary to return the motor current to its
24 maximum value. The duty cycle of the output pulses from
25 the generator 152 can also be manually controlled by
26 providing a potentiometer and capacitor in series across
27 pins 2 and 16 and removing the lead from pin 9.

28 Referring now to Figure 12, there is illustrated
29 a series of possible speed/torque curves for a brushless
30 DC motor with a maximum no-load speed of 10,000 rpm and
31 a stall torque of 83-inch ounces with full power applied
32 to the windings during each commutation period. See
33 curves 170 and 171 for this operation. Curves 172, 174,
34 176, 178 and 180 represent the speed/torque curves of
35 the motor where the generator is manually controlled to

supply signals of several different duty cycles to the gates 120, 122 and 124. Curve 182 represents the speed torque curve of the motor with the control signals applied to the gates 120, 122 and 124 from the circuit arrangement shown in Figure 11. As is illustrated, the curve is linear with the minimum current being provided at no load and maximum current being supplied to the motor windings just prior to stall. The following table illustrates the power consumption by the motor at points 1-6 in Figure 12 under load with a modulated control signal and a nonmodulated control signal.

Load Condition	Power, Watts			
	Modulated		Nonmodulated	
	Input	Loss	Input	Loss
1	3.0	3.0	3.0	3.0
2	6.3	3.2	6.8	3.7
3	8.2	3.3	9.3	4.4
4	15.2	3.8	25.8	14.4
5	11.2	3.8	44.8	37.4
6	3.9	3.9	55.4	55.4

As the above table illustrates, the use of a modulated control signal reduces the power considerably over the power that would be consumed by the motor if the windings were connected to the DC input power during the entire time that the commutation signals are present.

1 Figure 13 illustrates another embodiment of
2 the present invention in which the rate or speed of the
3 motor is controlled within a narrow range by turning off
4 the power to the windings when a maximum speed is
5 reached and turning the power back on when the speed has
6 dropped to a lower value. To provide this type of
7 control, the commutation pulse from phase 3 is applied
8 to the input of a J-K flip-flop 184 which provides an
9 output pulse that spans the leading edges of two posi-
10 tive commutation signals. Thus, the J-K flip-flop
11 produces one output pulse per revolution. The leading
12 edge of the output pulse from the J-K flip-flop triggers
13 a monostable multivibrator 186 which produces a refer-
14 ence pulse having a fixed time duration; i.e., Δt , that
15 is selected to be equal to the duration of the output
16 signal from the J-K flip-flop when the desired motor
17 velocity is reached. The positive output pulse from the
18 J-K flip-flop and the negative reference pulse from the
19 monostable multivibrator 186 are compared in an AND
20 gate 188. The output from the AND gate 188 will be
21 positive when the J-K output pulse has a longer time
22 duration than the output pulse from the monostable multi-
23 vibrator 186. The AND gate output is used to drive a
24 retriggerable multivibrator 190 which produces a
25 stretched output pulse of approximately three times the
26 time duration of the output from the monostable multi-
27 vibrator 186. As the motor increases in velocity, the
28 J-K flip-flop positive output pulse duration will
29 decrease in time. When the duration of this pulse is
30 equal to or less than the duration of the fixed refer-
31 ence pulse from the multivibrator 186, the output
32 (trigger) from the AND gate will decrease to zero. With
33 a zero voltage input, the output of the multivibrator 190
34 will time-out and go to zero. Upon receiving a zero
35 voltage signal from the multivibrator 190 the AND

1 gates 120, 122 and 124 (shown with only two inputs as in
2 Figure 10) will inhibit the commutation signal and the
3 drive signals to the drive transistors. The stator
4 current will then decrease to zero, causing the motor to
5 decelerate. With a slower motor speed, the J-K output
6 pulse will increase in time and generate an output
7 trigger which, when compared to the reference pulse,
8 will again provide a trigger to the multivibrator 190,
9 allowing the transistor drive signal to turn on the
10 drive transistors and supply current to the stator
11 coils. The motor will accelerate until it reaches its
12 maximum allowable speed as determined by the reference
13 pulse. The system will thus control the motor rate or
14 speed within prescribed limits.

15 Figures 14, 15 and 16 illustrate another
16 embodiment of the present invention in which the motion
17 of several motors is synchronized. The commutation
18 signals from the phases of each motor are supplied to OR
19 gates 194, 196 and 198. The output of the OR gates is
20 supplied to a signal synchronizer or microprocessor,
21 which in turn produces a step command pulse for each
22 phase of each of the motors. For example, the step
23 command pulses for phase 1 of each of the motors are
24 supplied on lead 200 to the phase 1 AND gate (i.e.,
25 120). The step command pulses for phases 2 and 3 are
26 supplied on leads 202 and 204 to AND gates for phases 2
27 and 3, respectively.

28 Referring now to Figure 15, there is illus-
29 trated the control circuitry for one motor used in the
30 synchronizing system of Figure 14. The leads 200, 202
31 and 204 are connected to the AND gates 120, 122 and 124
32 (shown with only two inputs), as discussed above. The
33 commutation signals (referred to in the figure as step
34 completion feedback signals) are illustrated as coming
35 from the terminals C-1, C-2 and C-3.

1 The AND gates for one phase of each of the
2 three motors of Figure 14 and the OR gate for that phase
3 are shown in Figure 16, along with the motor windings 40,
4 40' and 40" and drive transistors 72a/72b, 72a'/72b' and
5 72a"/72b" for that phase winding. The shaft position
6 signals for motors 1, 2 and 3 are designated RP-1, RP-1'
7 and RP-1", respectively. The OR gate 194 receives the
8 commutation signals C-1, C-1' and C-1" from phase 1 of
9 each of the motors 1, 2 and 3. The output of the OR
10 gate 194 controls the initiation of the next sequential
11 step command signal which cannot occur until the monitored
12 commutation signals from phase 1 of each of the motors
13 indicate completion of the commutation period. Power
14 will continue to be applied to any motor that has not
15 completed the commanded steps. However, as each indi-
16 vidual motor completes the step, its commutation signal
17 will automatically turn off the drive transistor and
18 then shut the power off to the associate phase winding.
19 The motor will then wait for the other units to catch up.
20 This permits the use of independent motors with different
21 output loadings and yet provides for synchronous motion
22 with never more than a single step difference.

23 There has been described a new and simple
24 system for controlling brushless DC motors which can
25 provide a wide variety of operations in response to low
26 level digital signals directly from signal generator
27 sources such as a computer or microprocessor. Various
28 modifications to the system will be apparent to those
29 skilled in the art without involving a departure from
30 the spirit and scope of the invention. For example,
31 where high inertia loads are to be driven by the motor,
32 dynamic braking may be utilized for removing excess
33 energy. To accomplish such braking additional stator
34 coils may be energized to apply opposing forces. Such
35 techniques are well known to those skilled in the art.

24/
-34-

BRUSHLESS DC MOTOR CONTROL SYSTEM
RESPONSIVE TO CONTROL SIGNALS
GENERATED BY A COMPUTER OR THE LIKE

ABSTRACT OF THE DISCLOSURE

A control system for a brushless DC motor responsive to digital control signals is disclosed. The motor includes a multiphase wound stator and a permanent magnet rotor. The motor is arranged so that each phase winding, when energized from a DC source, will drive the rotor through a predetermined angular position or step. A commutation signal generator responsive to the shaft position provides a commutation signal for each winding. A programmable control signal generator such as a computer or microprocessor produces individual digital control signals for each phase winding. The control signals and commutation signals associated with each winding are applied to an AND gate for that phase winding. Each gate controls a switch connected in series with the associated phase winding and the DC source so that each phase winding is energized only when the commutation signal and the control signal associated with that phase winding are present. The motor shaft may be advanced one step at a time to a desired position by applying a predetermined number of control signals in the proper sequence to the AND gates and the torque generated by the motor may be regulated by applying a separate control signal to each AND gate which is pulse width modulated to control the total time that each switch connects its associated winding to the DC source during each commutation period.

AWARDS ABSTRACT

Inventor: Douglas T. Packard

JPL Case No. 16420

CIT Case No. 1828

J&J Case No. JET1-E93

Date: May 7, 1985

Contractor: Jet Propulsion Laboratory

BRUSHLESS DC MOTOR CONTROL SYSTEM
RESPONSIVE TO CONTROL SIGNALS
GENERATED BY A COMPUTER OR THE LIKE

A system for controlling a brushless DC motor 14 by computer-generated digital control signals is disclosed. The motor includes a multiphase wound stator 18 and a permanent magnet rotor 17. The motor is provided with three phases and arranged so that each phase winding, when energized from a DC source, will drive the rotor through a predetermined angular position or step. A commutation signal generator (sensor elements 520-566 and comparator 80) responsive to the shaft position provides a commutation signal for each winding. A programmable control signal generator 130 such as a computer or microprocessor produces individual digital control signals for each phase winding. The control signals and commutation signals associated with each winding are applied to an AND gate 120, 122 or 124 for that phase winding. Each AND gate controls a switch connected in series with the associated phase winding and the DC source so that each phase winding is energized only when the commutation signal and the control signal associated with that phase winding are present. The motor shaft 16 may be advanced one step at a time to a desired position by applying a predetermined number of control signals (SC-1, SC-2, SC-3) in the proper sequence to the AND gates and the torque generated by the motor

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Contract No.	NADP-100
Contractor	Caltech/JPL
Inventor	9799
(City)	(State)

may be regulated by applying a separate control signal (TR-1, TR-2, TR-3) to each AND gate which is pulse width modulated to control the total time that each switch connects its associated winding to the DC source during each commutation period.

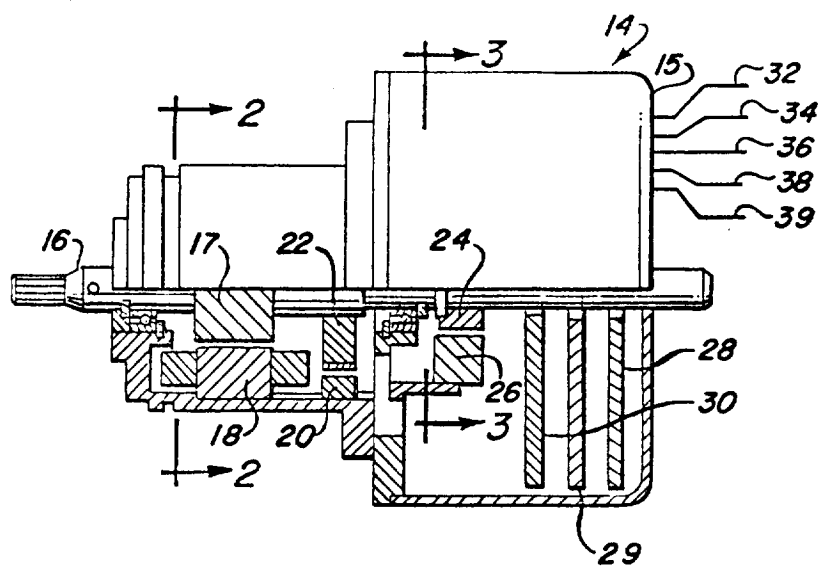


FIG. 1

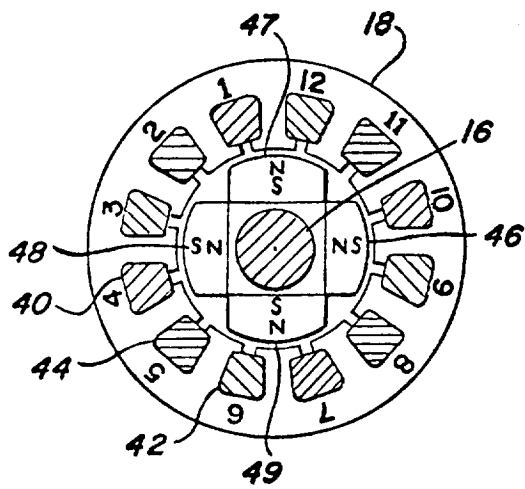


FIG. 2

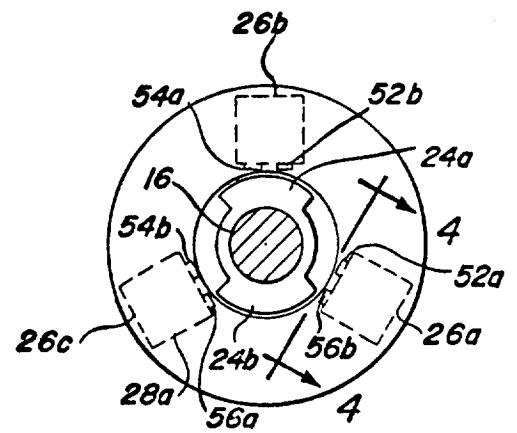


FIG. 3

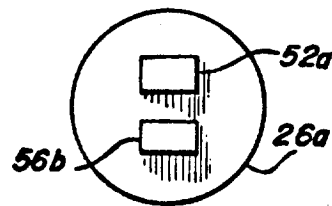
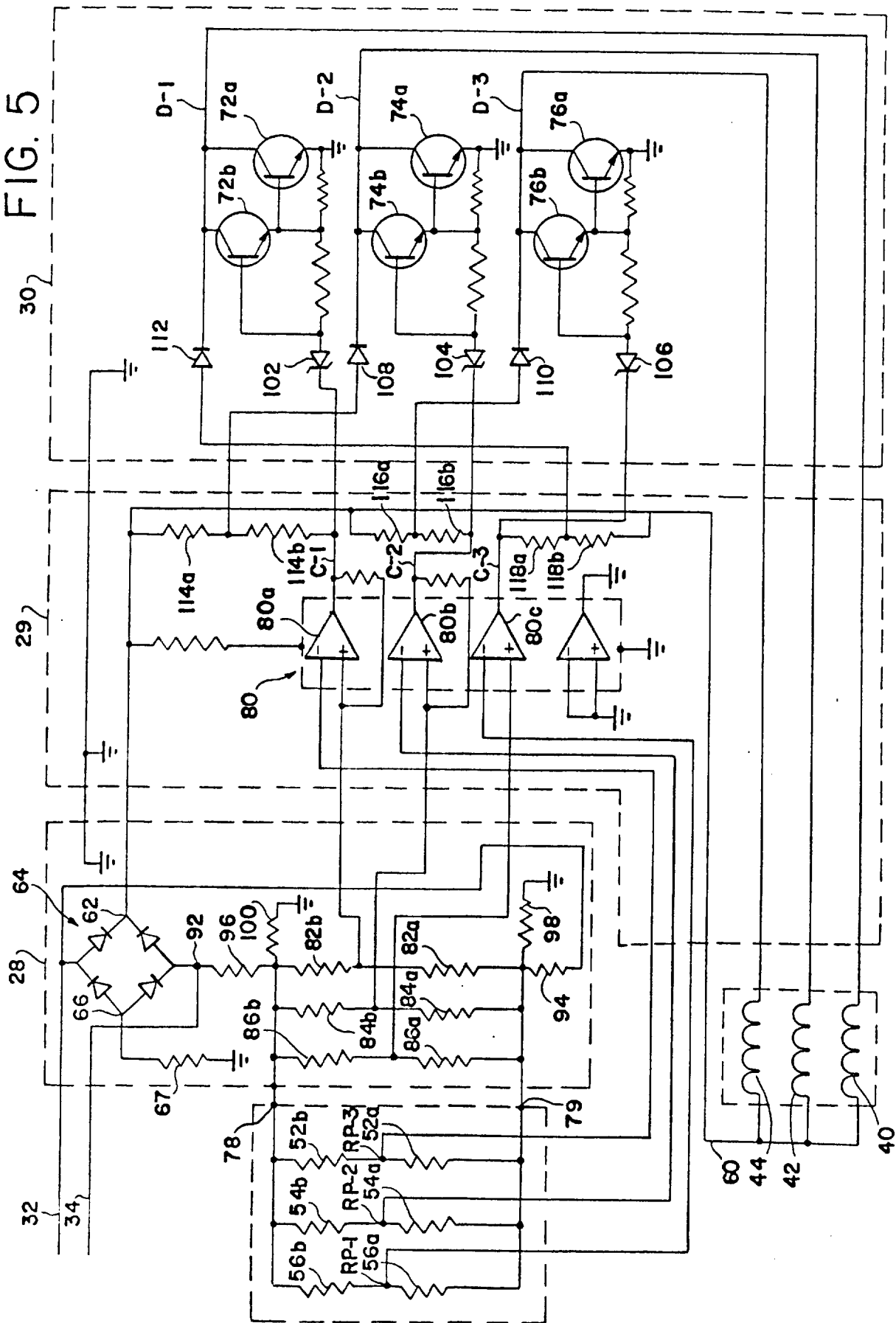


FIG. 4

FIG. 5



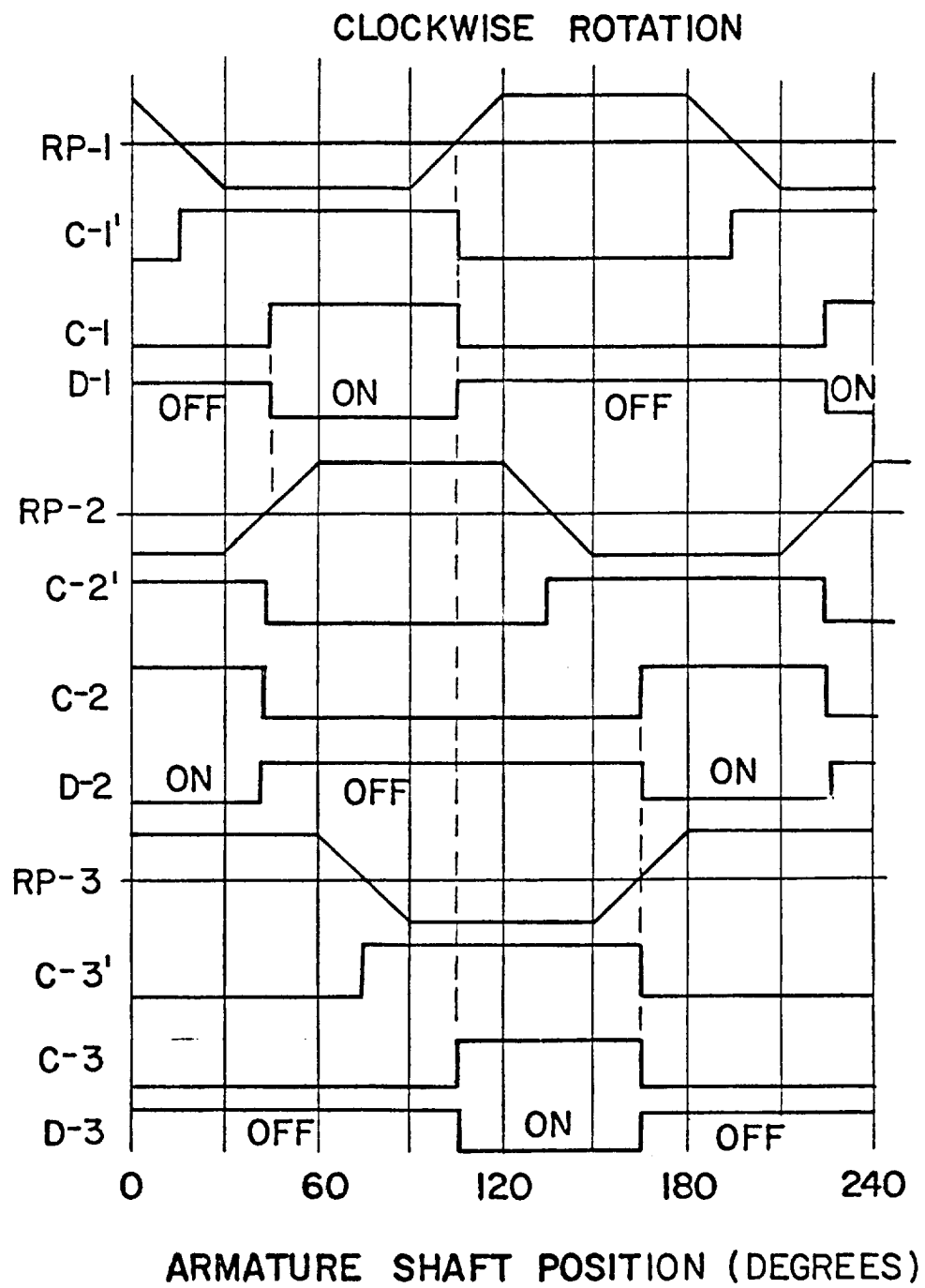
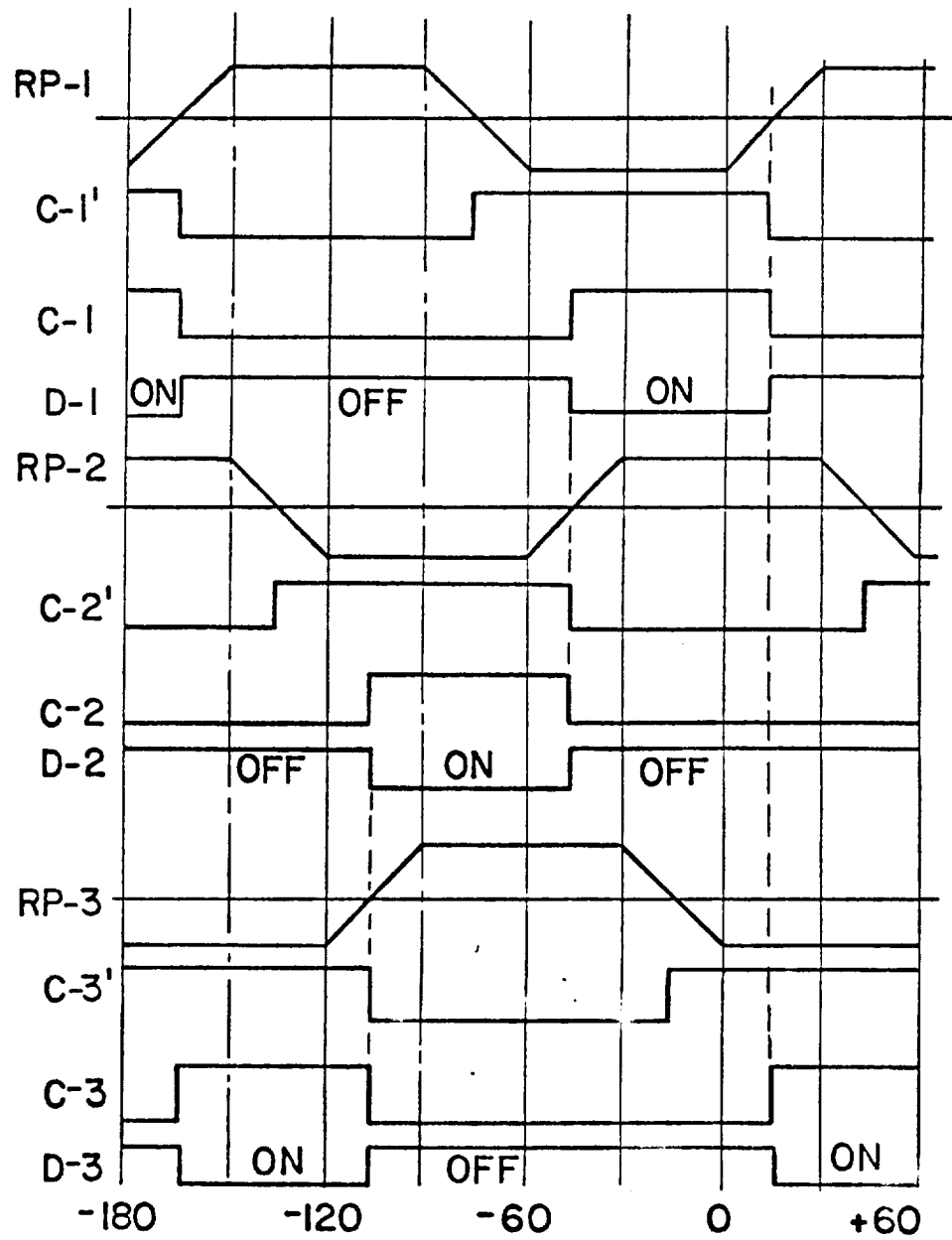


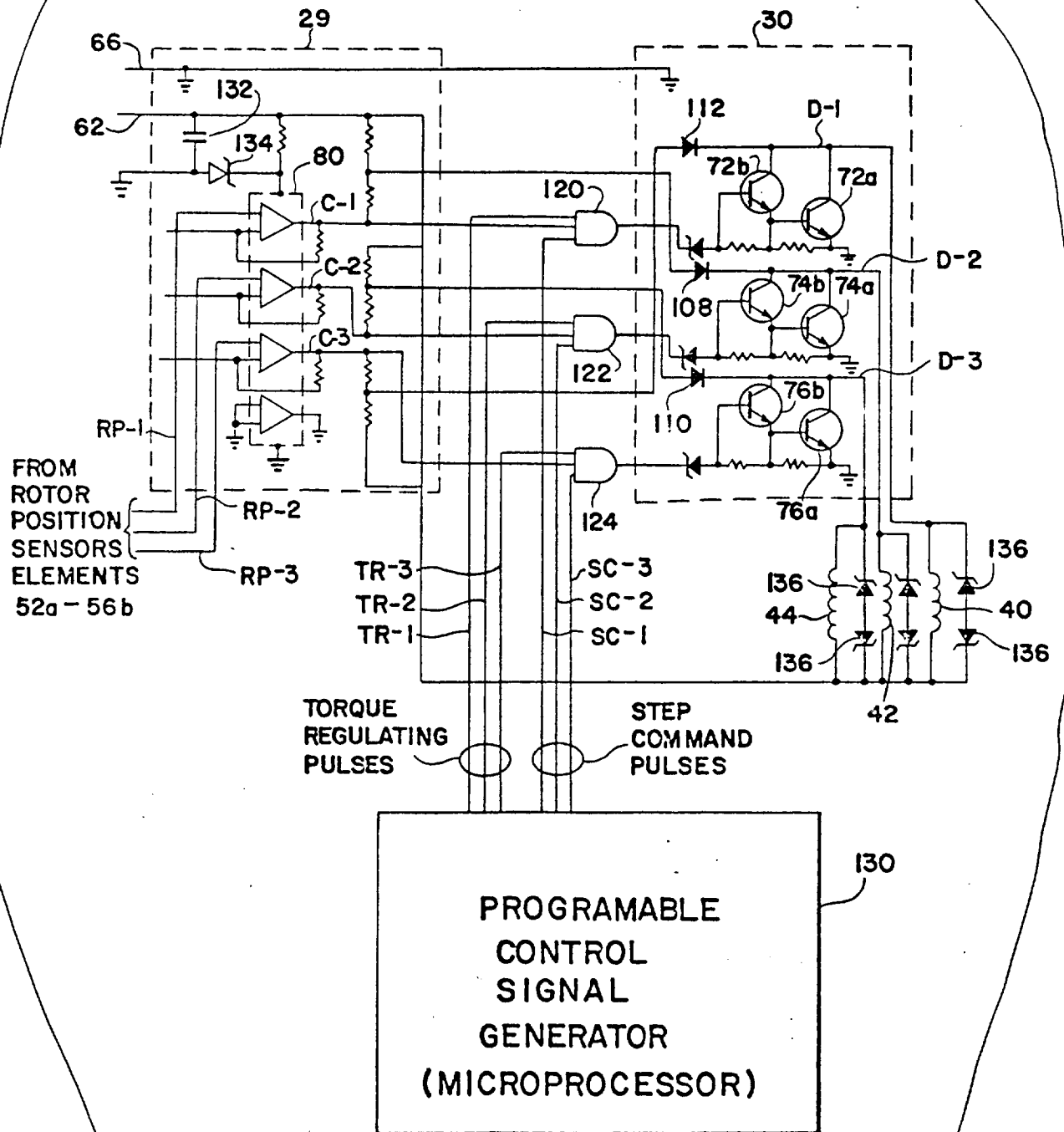
FIG. 6

COUNTER CLOCKWISE ROTATION

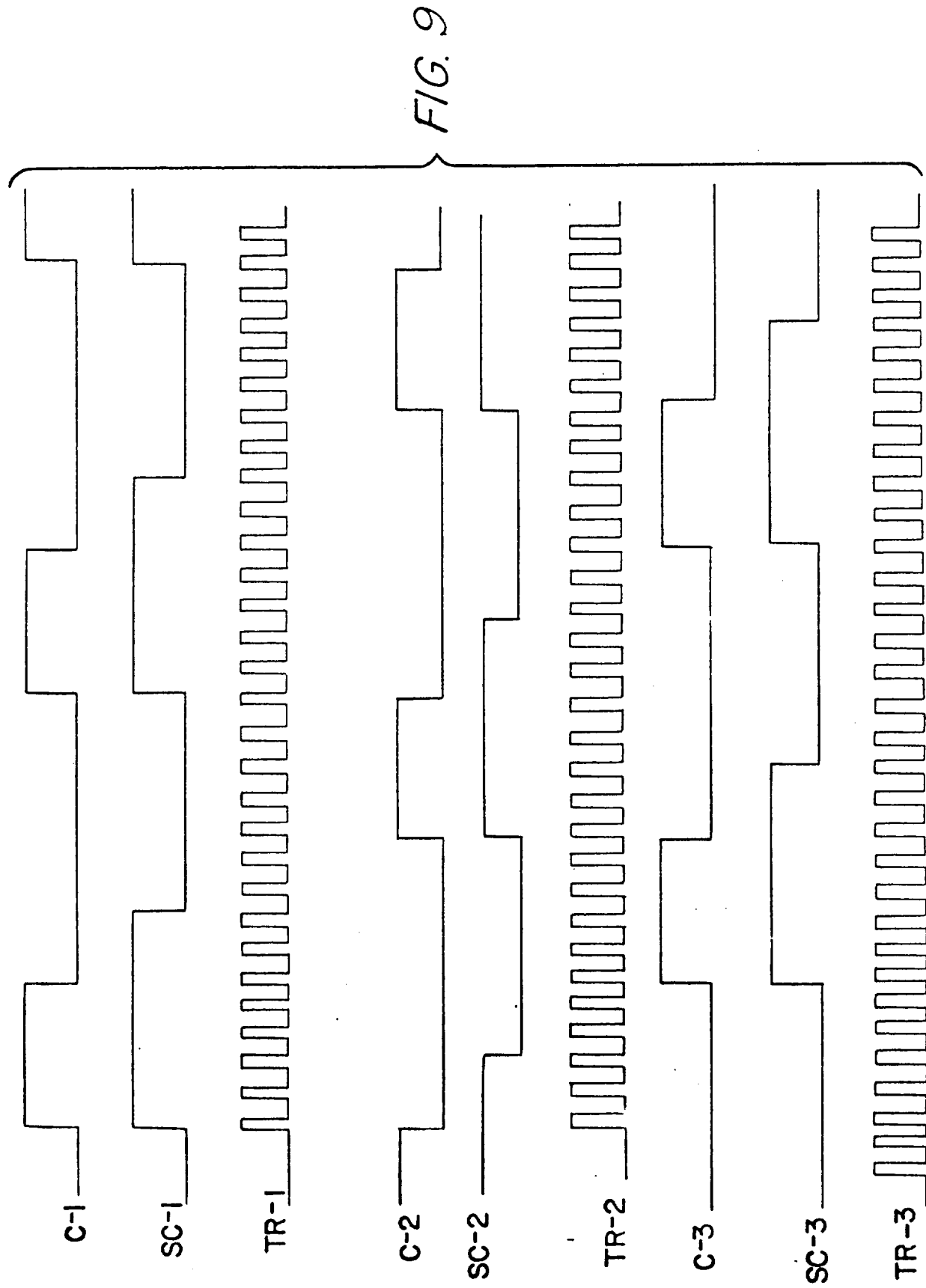


ARMATURE SHAFT POSITION (DEGREES)

FIG. 7



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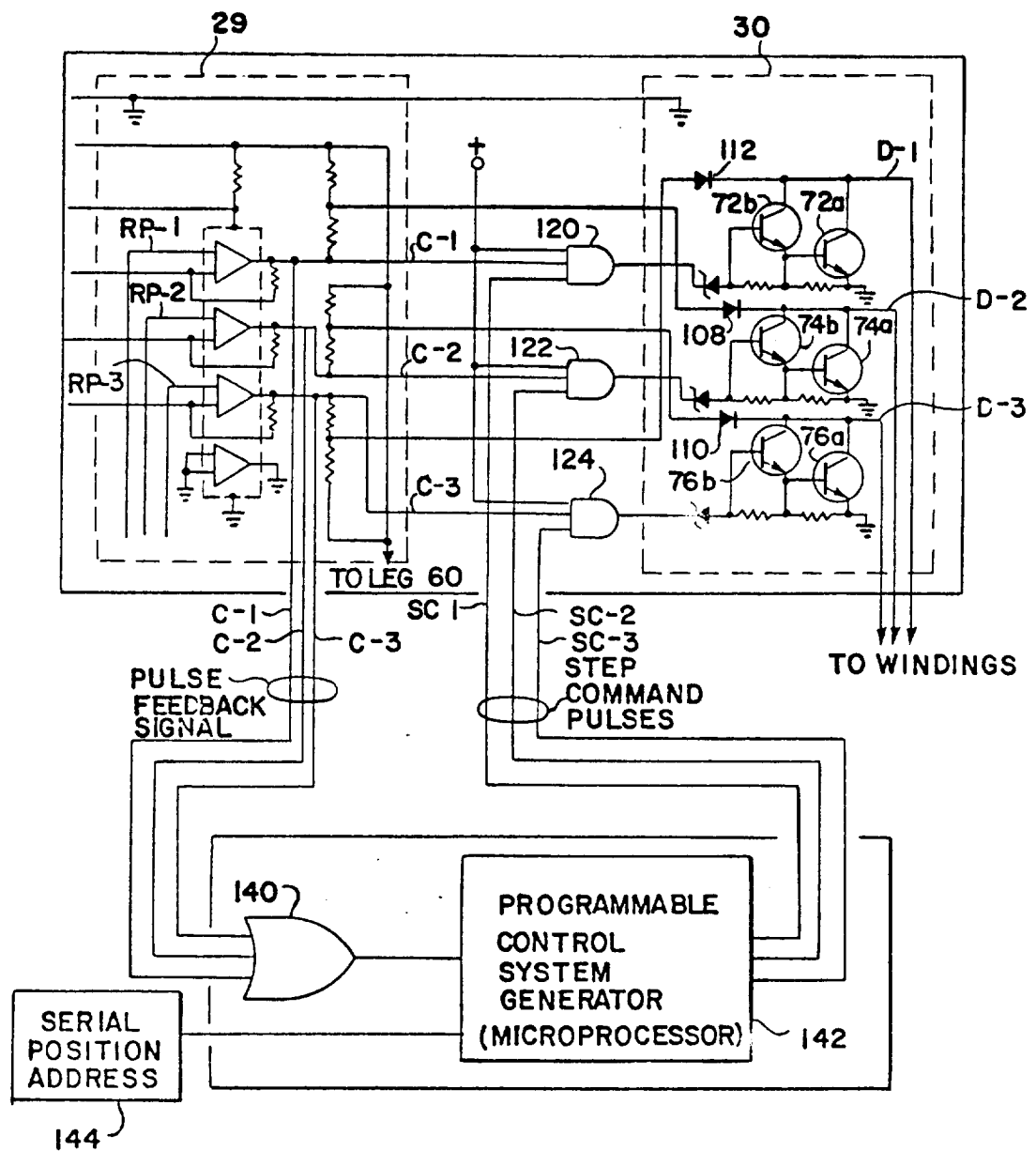
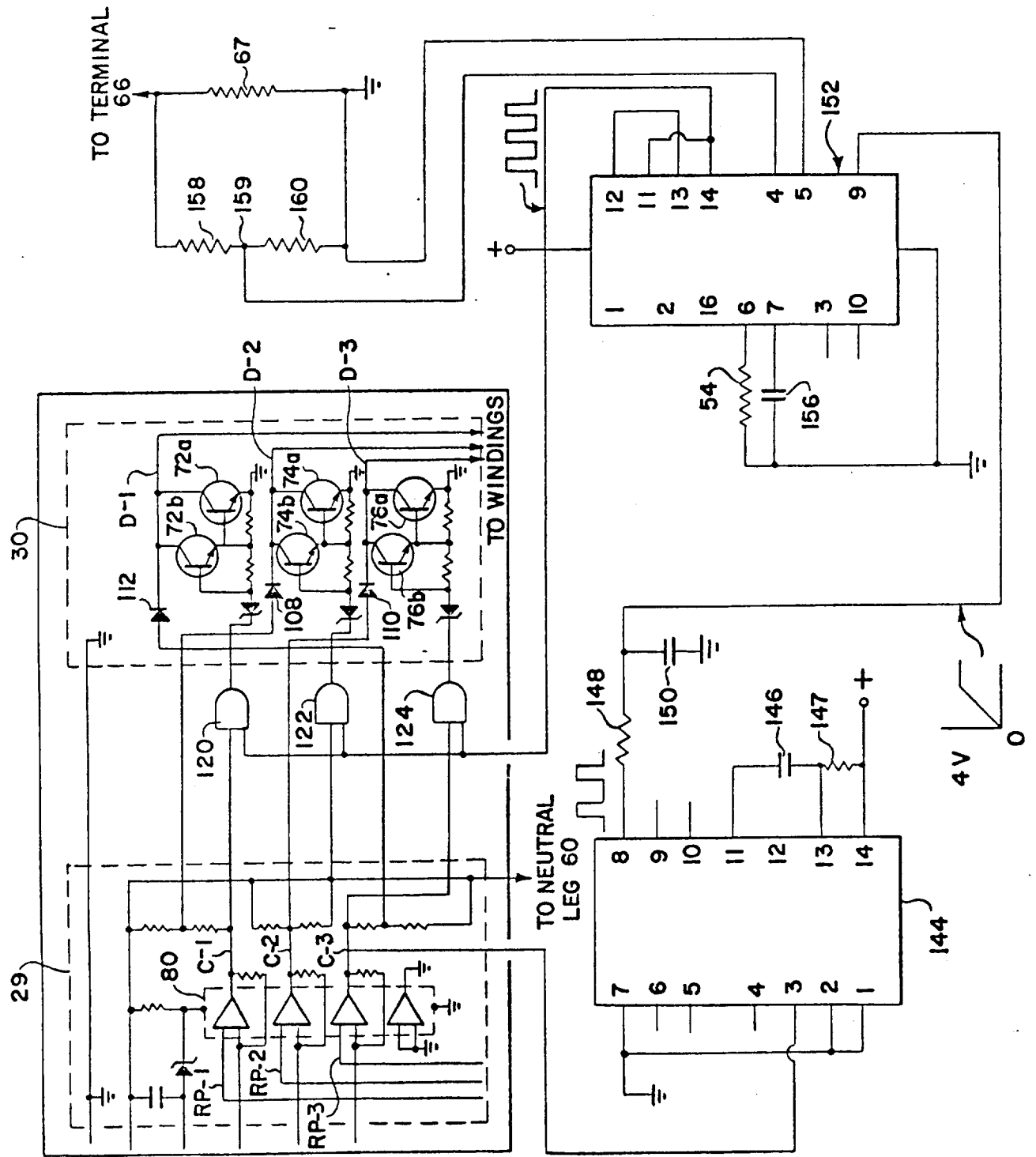


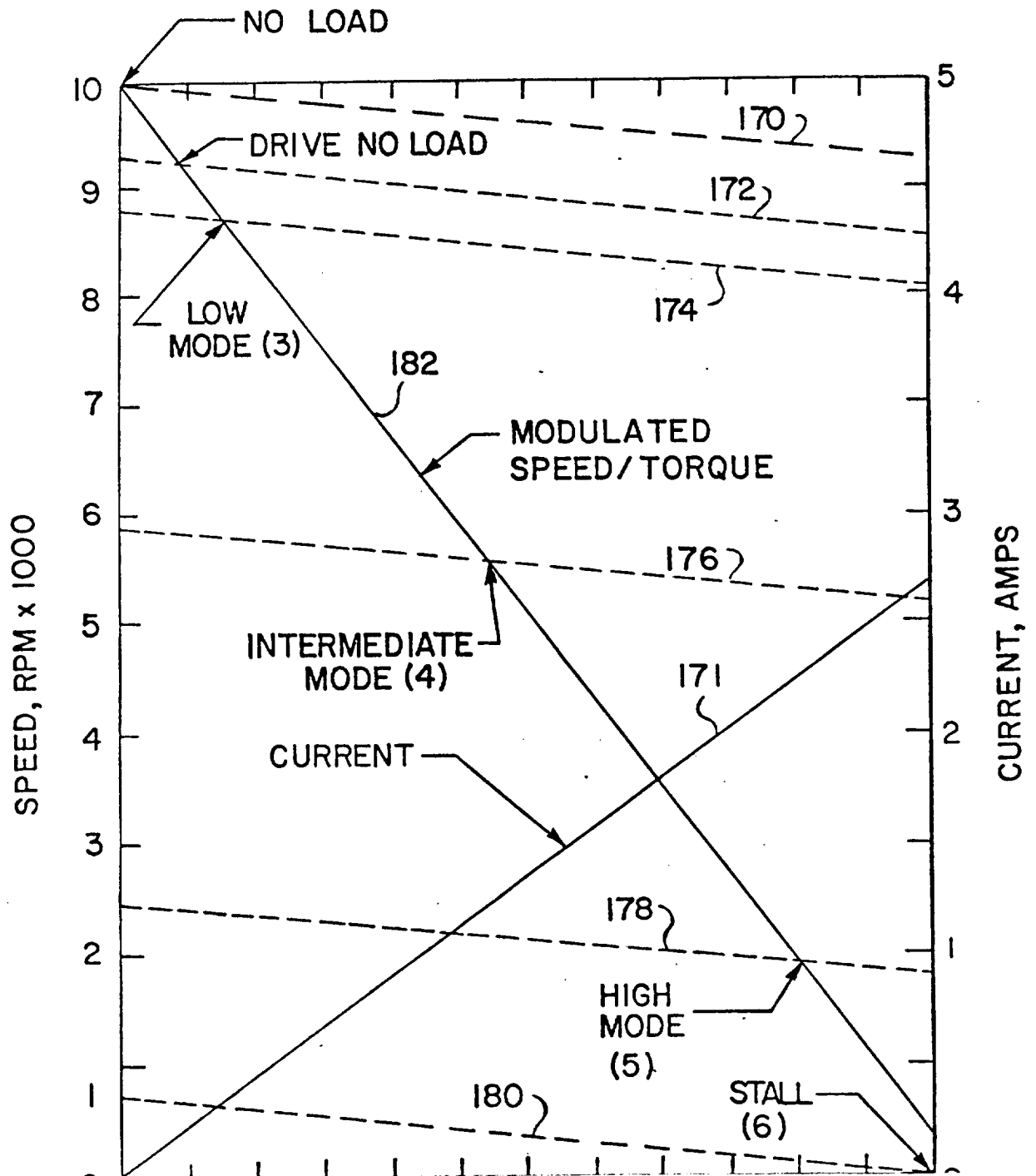
FIG. 10

FIG. 11



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FIG. 12



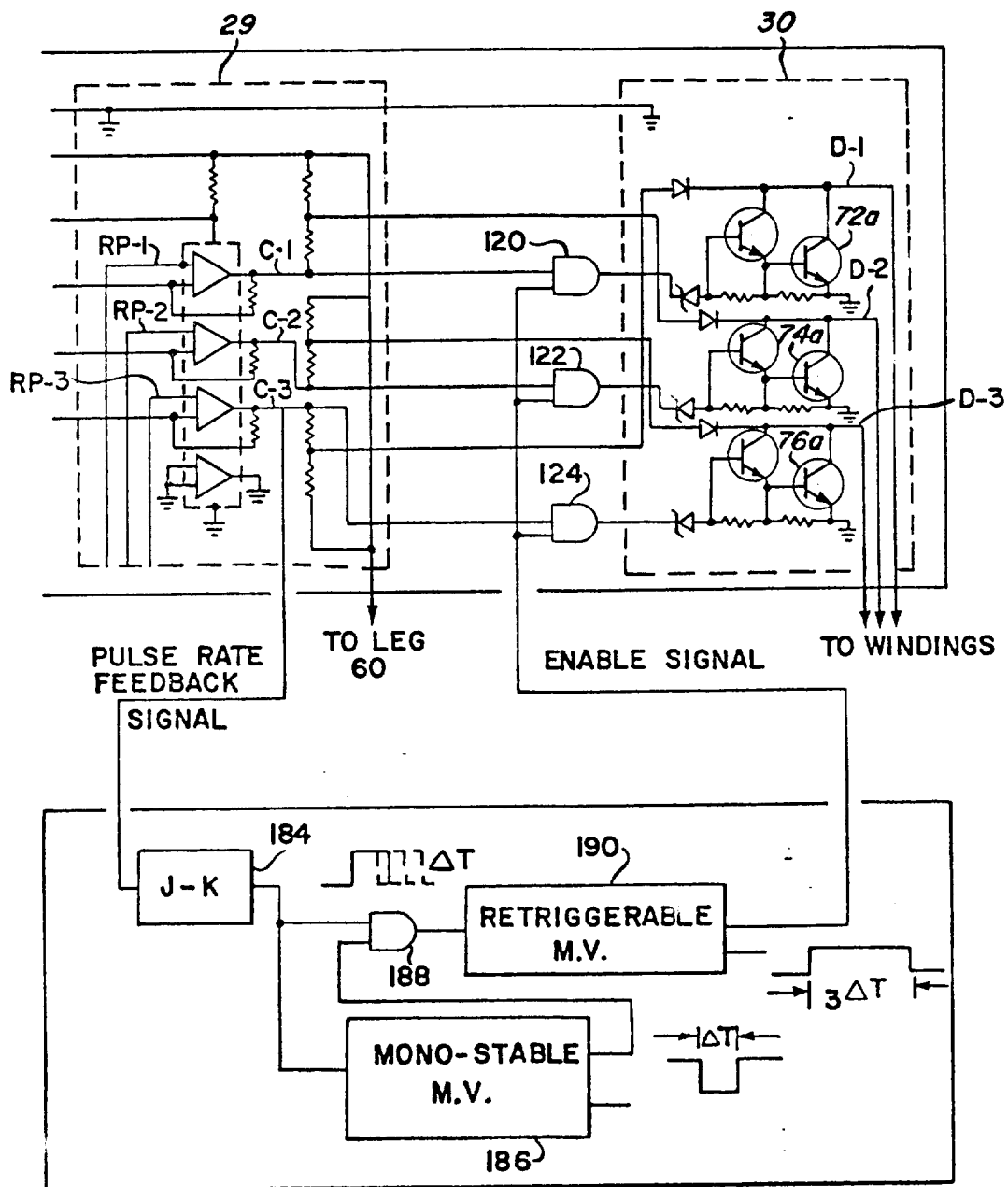


FIG. 13

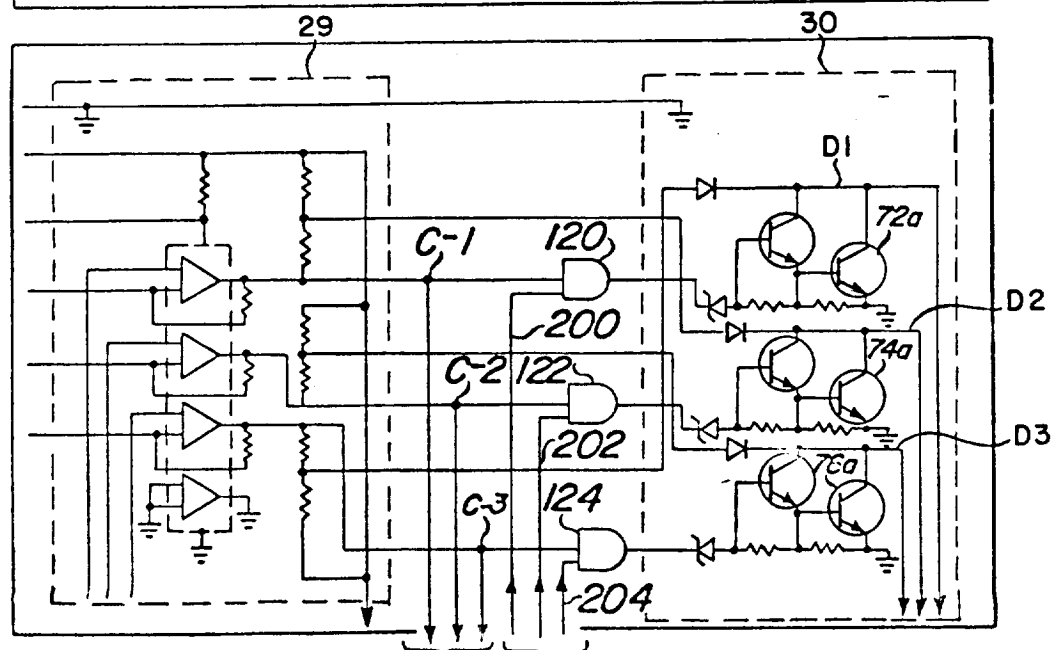
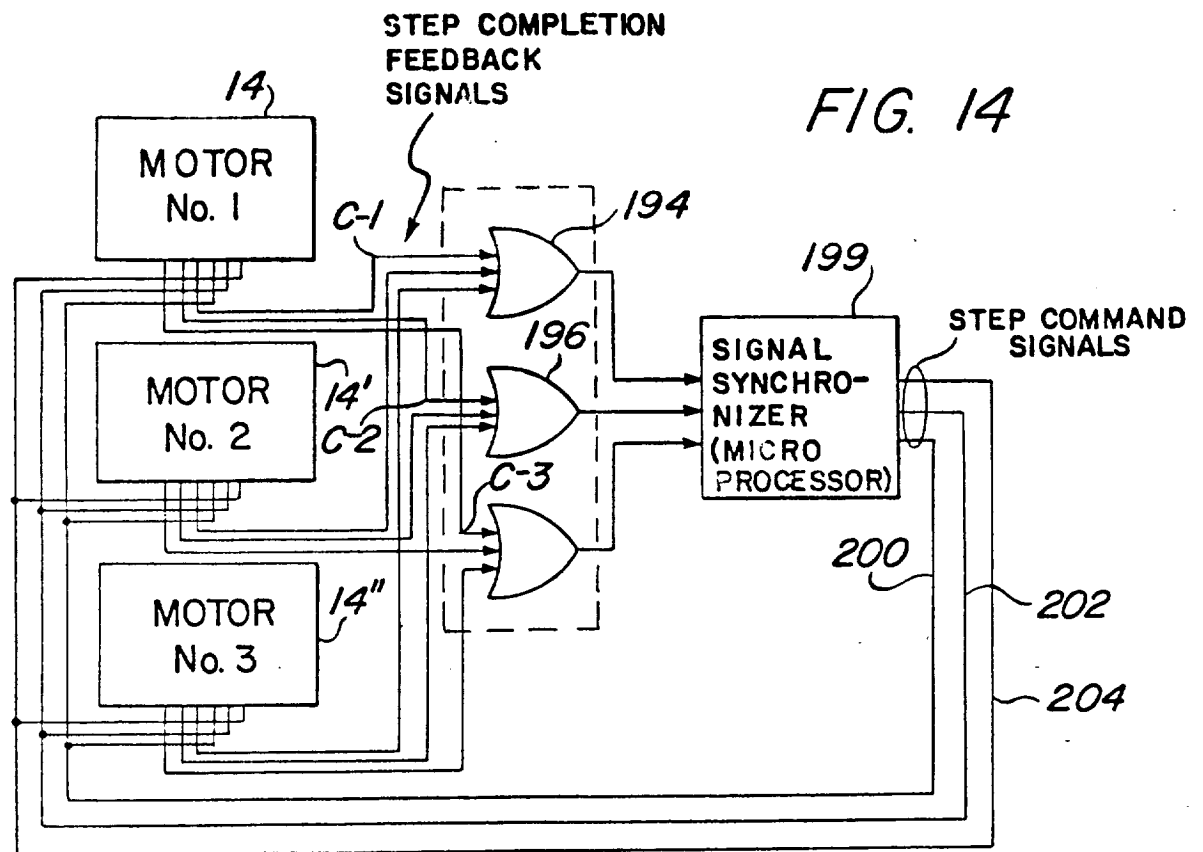


FIG. 15

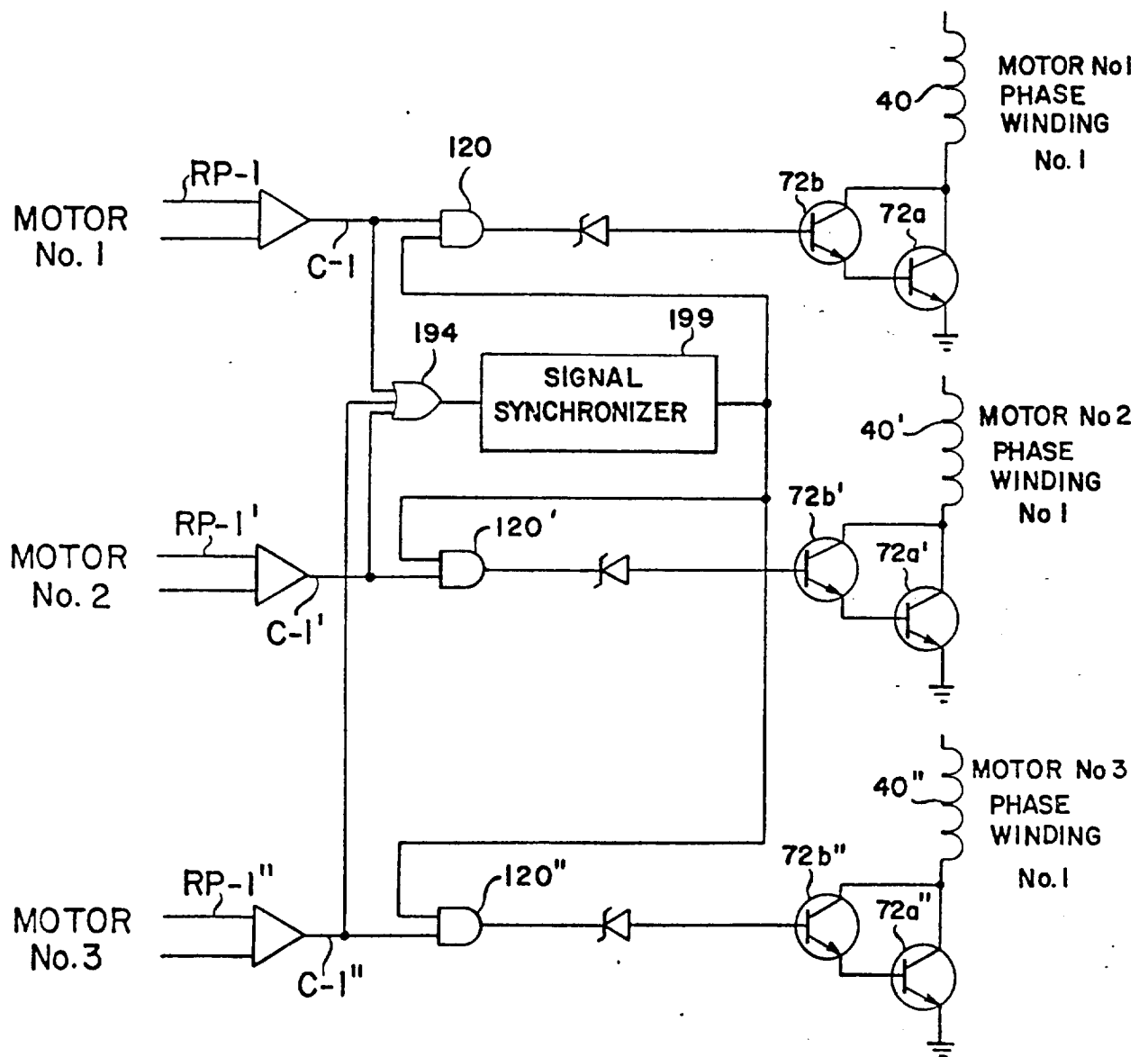


FIG. 16